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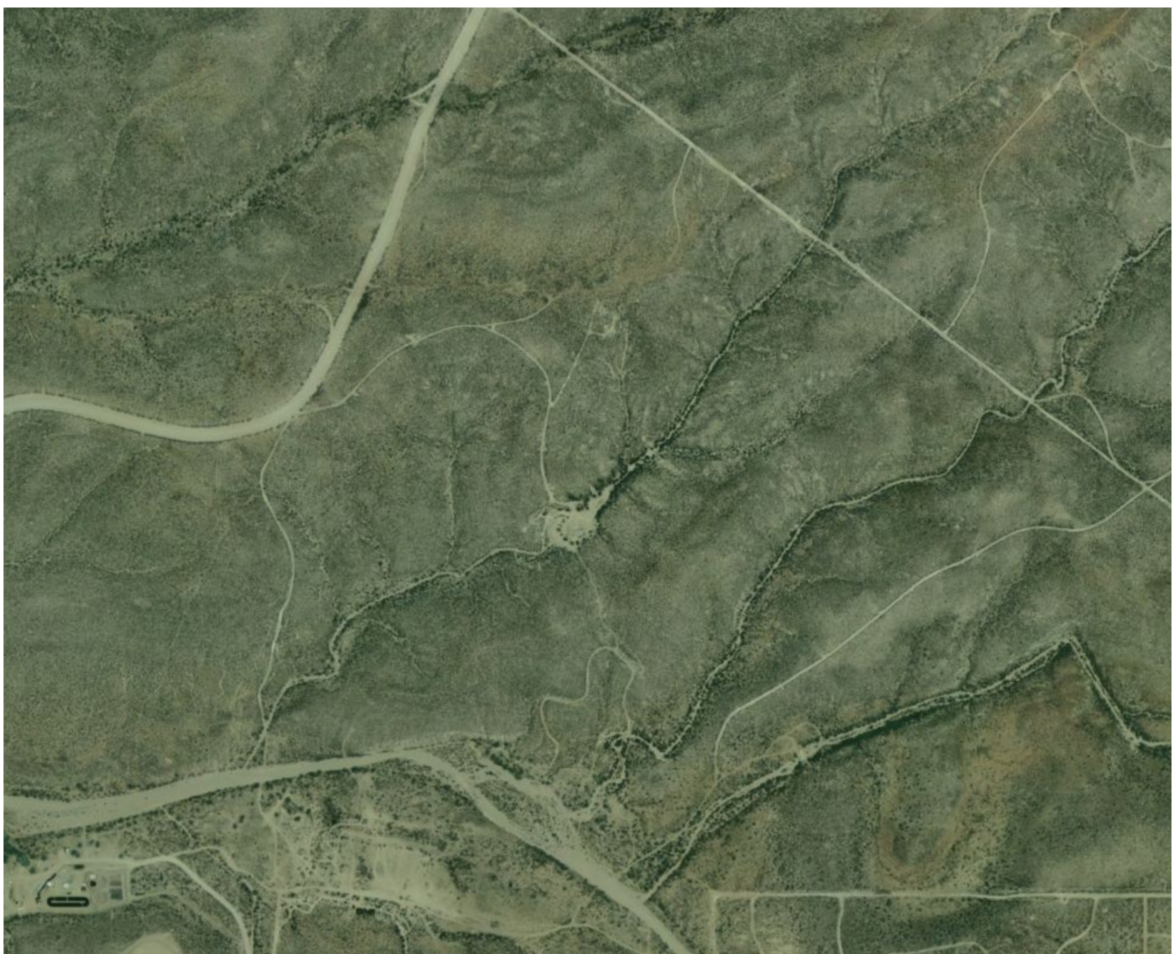

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Abstract

Seven 1-D sediment transport formulae are employed to predict coarse sediment transport in a low-order, ephemeral channel with patchy bed material. Sediment transport is modeled through two different methods to characterize the sediment supply: by using a channel-averaged grain-size distribution (GSD) and by using the mean GSDs from the relatively coarse and fine textured patches that compose the channel bed.

Modeling results show that the two different characterizations of the sediment supply produce significantly different values of predicted coarse sediment yield. The relative differences in the predicted yield values are dependent on the assumptions of each formula, including how the sediment supply is parameterized within the model. Modeled sediment yield values are contrasted to observed values for seven flashflood-type runoff events. The formulae accuracies typically are comparable to past analyses in fluvial systems more reminiscent of the hydraulic environments in which the models were derived (perennial flow, gravel-bed material).

Study results reaffirm that the method by which sediment supply is characterized significantly impacts the performance of sediment transport formulae and that a single GSD might not adequately describe the sediment supply originating from patchy beds.

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Preface

This research was conducted between 2004 and 2011 by personnel of the U.S. Army Engineer Research and Development Center (ERDC), Geotechnical and Structures Laboratory (GSL), Vicksburg, Mississippi, and scientists of the USDA Agricultural Research Service Southwest Research Center, Tucson, Arizona.

Dr. Brendan T. Yuill of the Geotechnical Engineering and Geosciences Branch (GEGB) prepared this report. At the time of publication, Danny Harrelson was Acting Chief, GEGB; Dr. Bartley P. Durst was Chief, Geotechnical and Structures Division (GSD); Dr. William P. Grogan was Deputy Director, GSL; and Dr. David W. Pittman was Director, GSL.

COL Kevin Wilson was Commander and Executive Director of ERDC. Dr. Jeffery P. Holland was Director.

Definitions

F_s = fraction of the bed sediment composed of sand [%].
g = acceleration due to gravity (9.81 m s^{-1} s^{-1}).
D_i = diameter of the grain-size the transport rate is being calculated for [m].
D_m = mean grain size of the grain-size distribution of the surficial channel bed sediments [m].
D_{16} = the grain size of which 16 % of the local GSD is finer [m].
D_{50} = median grain size of the grain-size distribution of the surficial channel bed sediments [m].
D_{84} = the grain size of which 84 % of the local GSD is finer [m].
u^* = instantaneous shear velocity of flow [m s^{-1}].
q = flow discharge per unit width [m^3 s^{-1} m^{-1}].
q_c = critical flow discharge per unit width [m^3 s^{-1} m^{-1}].
Q_p = peak discharge per flow event [m^3 s^{-1}].
q_s = volumetric sediment transport rate per unit width [m^3 s^{-1} m^{-1}].
$q_s{}^*$ = $q_s / [(RgD_i)^{0.5} D_i]$ = dimensionless volumetric sediment transport rate per unit width [-].
R = specific gravity of a sediment grain in water [-].
R_h = hydraulic radius [m].
S = channel bed slope [m m^{-1}].
t_i = duration of temporal interval i [s].
T_r = return interval [yrs].
$\sigma_0(\phi_{sgo}), \omega_0(\phi_{sgo})$ = strain functions defined in tables within Parker (1990).
τ = boundary shear stress [N m^{-2}].
τ_I = mean boundary shear stress for temporal interval i [N m^{-2}].
τ_c = critical boundary shear stress [N m^{-2}].
$\tau_{CE} = \sum [(\tau_i - \tau_c) * t_i]$ = cumulative excess boundary shear stress [N m^{-2}].
τ_p = peak boundary shear stress per flow event [N m^{-2}].
τ^* = $\tau / \rho g R D_i$ = dimensionless boundary shear stress [-].
$\tau_c{}^*$ = $\tau_c / \rho g R D_i$ = dimensionless critical boundary shear stress [-].

1 Introduction

One-dimensional models of riverbed sediment transport typically predict flux based on inputs of flow strength and a sediment supply (Parker 2007). Flow strength is commonly characterized in terms of discharge, excess shear stress, or excess stream power. The sediment supply is commonly characterized by its grain-size distribution (GSD), summarized in terms of a single channel-averaged GSD for the fraction of the channel bed that is acting as a source of entrainable sediment (Almedeij and Diplas 2003). Early models often required inputs of a simple descriptive statistical value of the GSD, such as the median (i.e., D_{50}) or mean grain size. More recently, models have been derived that require inputs of a full GSD, which better account for the range of grain sizes within the sediment mixture.

While a single GSD has been shown to describe the sediment supply in many fluvial channel systems well, there is concern that this type of characterization might not accurately describe the sediment supply in channel reaches with patchy bed material (Yager et al. 2007; Mueller et al. 2008; Yuill 2010). In patchy beds, the bed material is arranged through various natural sorting processes into discrete patches of relatively homogeneous GSD*s* that are significantly different from proximal patches within a single reach (Buffington and Montgomery 1999). These types of patchy beds have been observed in many types of alluvial channels, and are generally assumed to be the product of local divergences in transport competence and capacity as well as sediment supply (Dietrich et al. 2005).

A single channel-averaged GSD might not adequately characterize the sediment supply dynamics that take place within patchy beds and, for two primary reasons, does not meet the requirements to accurately model bed material transport.

The first reason is that sediment might be preferentially entrained from one patch relative to another. Holding other influences constant (e.g., local boundary shear stress, bed roughness), patches composed of finer material will experience during competent flows higher rates of grain entrainment and transport than coarser patches (Paola and Seal 1999). Previous research on bed material patches has shown that fine patches could contribute the majority of sediment measured in transport during high-frequency flow events (Lisle and Madej 1992; Garcia et al. 1999; Vericat et al. 2008). In these circumstances, it might be unnecessary to treat the grains located in the coarse patches as an equally significant sediment source as the grains located in fine patches.

The second reason is that the entrainment of a specific grain is influenced by the relative size of its neighboring grains (Andrews 1993; Parker 1990). Coarser neighboring grains might decrease the mobility of smaller grains immediately downstream by shielding them from the drag force of the flowing water. Smaller grains might increase the mobility of proximal coarse grains by reducing the angle of repose for the coarse grains and by reducing the local mean channel roughness (Dietrich and Whiting 1989; Wilcock and Crowe 2003). The effect of the local GSD on grain mobility might not be adequately captured if the patch GSDs are significantly different than the channel-averaged GSD.

This study employs seven sediment transport models (six bed load formulae and one total load formula) to calculate coarse sediment (i.e., grain sizes ≥ 2.0 mm in diameter) transport in the Lucky Hills 104 watershed, a low-order, ephemeral watershed in semiarid Arizona, during a series of runoff events. Following a previous study by Mueller et al. (2008), sediment is modeled using two different supply scenarios, where the sediment supply is set as the channel-averaged GSD, and where the sediment supply is set as the mean GSDs of two types of bed patches differentiated by relative texture (fine or coarse). Mueller et al. (2008) found that, in a low-ordered, perennial channel, bed load formulae performed most accurately when the sediment supply was set as the GSD of the fine bed patches, concluding that this was the area of the channel bed contributing the vast majority of the sediment measured in transport during the small flood events.

This study employs a similar modeling experiment in a more mobile channel-bed substrate, where the majority of the bed material is likely entrained during a series of observed flow events. Further, this study employs bed load formulae that explicitly consider the effect of the local GSD on grain mobility and transport, in addition to formulae that consider a single summary grain size. The predicted values of sediment transport are compared to each other and to measured values of coarse sediment yield.

The results of this analysis shed light on the applicability of characterizing patchy beds by a single GSD, as compared to explicitly accounting for the presence of the patches when employing sediment transport formulae to model the transport of bed material in fluvial channels.

2 Study Area

The Lucky Hills 104 watershed is a 4.53 ha sub-watershed within the Walnut Gulch Experimental Watershed in southeast Arizona (Figure 1). Walnut Gulch has been monitored for precipitation, runoff, and sediment transport since the 1950s, although bed load transport has only recently become a topic of study (Yuill and Nichols, in press; Nichols, in review; Renard et al. 2008).

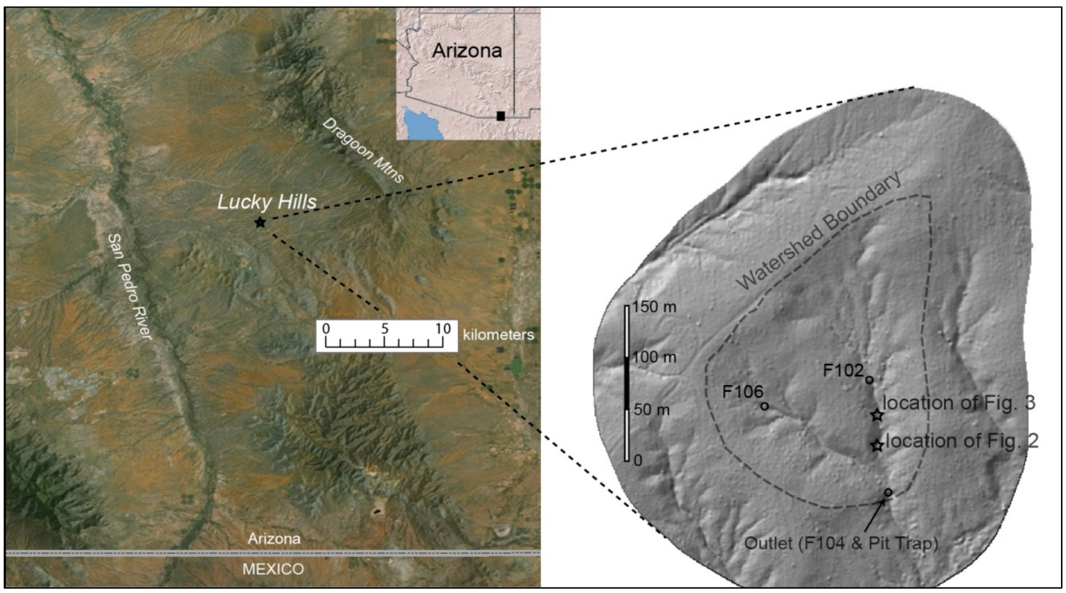

Figure 1. Map of the Lucky Hills watershed and surrounding area.

The Lucky Hills slopes are populated with drought-resistant vegetation, including creosote bush, white thorn acacia, and tarbush. Mean temperatures in Walnut Gulch range from 22˚C in January to 33˚C in July. The mean annual precipitation at Lucky Hills is approximately 300 mm, with the majority occurring during the summer monsoon season, July to September (Goodrich et al. 2008). Surface runoff is predominately a result of convective summer thunderstorms that are characterized by brief periods, on the order of a few hours, of intense precipitation. Using the historical flow data dating to 1963 (http://www.tucson.ars.ag.gov/dap), the calculated peak discharges for the flow events with 2-, 10-, and 50-year reoccurrence intervals are 0.35 $m^3 s^{-1}$, 0.86 $m^3 s^{-1}$, and 1.27 $m^3 s^{-1}$, respectively, based on a Log-Pearson Type III distribution. The mean flow event at Lucky Hills 104 has a duration of less than one hour, a peak discharge of 0.15 $m^3 s^{-1}$, and a volume of 100 m^3.

The channel network within Lucky Hills 104 lies primarily downstream of two internal flumes, F106 and F102. Upstream of F106 and F102, channelized runoff occurs in rills with unstable channel dimensions and orientation. The channel width within the stable channel network ranges from 0.5 to 2.0 m. The gradient of the channel banks normal to the direction of stream flow ranges from approximately 20% to near vertical for short reaches. Figure 2 illustrates a typical channel reach approximately 30 m upstream of the watershed outlet. The mean longitudinal slope of the stable channel network is 0.027 m m^{-1}. The channel bed material is an "extremely poorly sorted" (Folk and Ward 1957) sand-gravel substrate. The bed material is arranged in patches of more homogeneous GSDs that vary in size from fractions of a square meter to tens of square meters (Figure 3). These patches may be differentiated into two categories, those primarily composed of sand and those primarily composed of gravel. A study by Yuill et al. (2010) found that the coarser gravel patches remained relatively stable in size and location over time, despite the fact that patch grains were commonly mobilized by flow. As found in other dryland drainage networks (Laronne et al. 1994), the channel bed shows no consistent trend of bed armoring or vertical stratification in mean grain size (Yuill 2010).

Figure 2. Photograph of a representative channel reach.

Figure 3. Photographic map of a section of the Lucky Hills channel bed without (A) and with (B) the patch boundaries delineated.

Since Lucky Hills is a headwater watershed, its slopes and channel bed are the source of the vast majority of the fluvial sediment transport. The local drainage network is incising into a Holocene alluvial veneer covering the Whetstone Pediment, a gentle transport slope composed of Gleeson Road Conglomerate, underlying much of north-central Walnut Gulch (Gilluly 1956; Osterkamp 2008). The Gleeson Road Conglomerate near the Lucky Hills region is a poorly to well cemented basin fill of Plio-Pleistocene plutonic or volcanic clasts approaching 900 m in thickness. Surficial sediments were likely weathered from the granitic Dragoon Mountains located approximately 15 km to the east. The slopes are covered in a well-developed erosional pavement of rock fragments that average 16 to 32 mm in diameter, covering a finer substrate with a mean diameter of approximately 3 mm (Canfield et al. 2001).

3 Methodology

Prediction of bed load sediment transport

Seven sediment transport formulae were selected to model coarse sediment yield for this analysis. They represent a range of one-dimensional predictive models commonly employed in contemporary river research, engineering, and management applications, each with unique physical assumptions (Table 1). A description of each formula is below.

Table 1. List of the sediment transport formulae evaluated during this study. See the Definitions page at the beginning of the report for an explanation of each variable used.

Formula	Abbrev.	Equations	Comments
Wilcock and Crowe (2003)	WC	see appendix for full set of equations.	-parameterized w/full GSD. -contains hiding function. -considers effect of sand. -based on laboratory obs.
Parker (1990)	Parker	see appendix for full set of equations.	-parameterized w/full GSD. -contains hiding function. -derived from field obs., in a perennial gravel-bed river.
Powell, Reid, and Laronne (from Parker, 2007)	PRL	see appendix for full set of equations.	-parameterized w/full GSD. -contains hiding function. -derived from field obs., in an ephemeral gravel-bed river.
Meter-Peter and Muller (1948)	MPM	$q_s{*} = 3.97(\tau{*}-\tau_c{*})^{1.5}$	-parameterized w/D_m. -widely used in application. -derived from field obs., in a seasonal/perennial gravel-bed river.
Bagnold (1956)	Bagnold	$q_s{*} = 4.25\tau{*}^{0.5}(\tau{*}-\tau_c{*})$	-parameterized w/D_{50}. -based on excess stream power. -based on laboratory obs.
Schoklitsch (1950)	Schoklitsch	$q_s{*} = 2500S^{1.5}(q-q_c)\rho_s^{-1}$ $q_c = 0.26R^{1.67}(D_{50}^{1.5}\ S^{-1.16})$	-parameterized w/D_{50}. -based on '"excess discharge". -derived from field obs., in perennial gravel-bed rivers.
Engelund-Hansen (1967)	EH	$q_s{*} = 0.05(\tau{*})^{2.5}\,C_f^{-1}$	-parameterized w/D_{50}. -estimates total load transport. -based on laboratory obs.

The Parker (1990) formula (Parker)

The *Parker* formula calculates the total bed load transport rate as a summation of the transport rate for each grain-size fraction within the surface substrate of the channel bed. The set of equations composing the formula incorporates a hiding function designed to account for the effect of the local GSD on the mobility of each particular grain size present, decreasing the mobility of relatively fine grains and increasing the mobility of relatively large ones. The *Parker* formula was derived from a large sediment transport database chronicling observations at Oak Creek, a perennial, gravel-bed stream in Oregon (Milhous 1973). The channel bed exhibited a well-defined armor layer of grains much coarser than the underlying substrate material that only became fully entrained at flows reaching the bank-full stage. Sand (i.e., grain sizes finer than 2.0 mm) comprised a negligible fraction of the channel bed material and was excluded from the derivation of the transport formula; therefore, the formula is assumed not applicable for modeling its transport.

The Wilcock and Crowe (2003) formula (WC)

The *WC* formula, like the *Parker* formula, calculates a fractional transport rate for each grain size represented within surface GSD of a channel bed and accounts for grain hiding effects. The *WC* formula is applicable to sand and gravel channels by explicitly accounting for the effects of sand within the bed matrix. The formula was derived from flume experiments using sediment mixtures of variable grain-size distributions, both unimodal and bimodal. The proportion of sand within the channel bed was found to increase the mobility of all grain sizes present.

The Powell, Reid, and Laronne formula (PRL)

The *PRL* formula is based on the formulation of a predecessor of the *Parker* (1990) formula, derived in *Parker* (1978). A review of the *PRL* formula appears in *Parker* (2008). The sediment transport relation used in this formula is computed using field data measured from an ephemeral gravel-bed channel, the Nahal Eshtemoa in the Negev Desert, Israel, reported in Powell et al. (2001). The Nahal Eshtemoa, as is common in many other dryland channels, lacks the vertical stratification of bed material texture present in armored channels.

The Meyer-Peter and Müller (1948) formula (MPM)

Due to its relative simplicity, the *MPM* formula has been a popular bed load predictor in both research and engineering applications since its derivation in 1948 (Martin-Vide et al. 1999). It computes bed load discharge based on the mean grain size of a sediment mixture and values of excess instantaneous boundary shear stress for that grain-size class. The formula is derived from laboratory experiments of both uniform and mixed grain-size distributions under steady, uniform flow conditions. This study employs a reformulation of the 1948 *MPM* formula by Wong and Parker (2006) that corrects an error in the original relation that led to overestimated transport rates in plane-bed conditions.

Bagnold (1956) formula (Bagnold)

The *Bagnold* formula equates sediment transport as work done by the flow of water. The energy available to transport sediment is set as cross-section averaged stream power. The formula calculates a total bed load transport rate (moving within the active layer of the channel bed) based on a single representative grain size for the bed material GSD, such as D_{50}.

Schoklitsch (1950) formula (Schoklitsch)

The *Schoklitsch* formula is a commonly used bed load equation that relates sediment flux with an excess flow discharge rate. The formula was derived from multiple flume experiments, including those carried out by G.K. Gilbert (1914), and was initially verified with field measurements from the Danube and Terek rivers in Eastern Europe. The GSD of the sediment supply is parameterized within the model using the D_{50} value.

Engelund-Hansen (1967) formula (EH)

The *EH* formula predicts the transport of bed material transported as bed load and in suspension based on simple metrics of shear stress and hydraulic resistance. The formula was derived from laboratory data (Guy et al. 1966) and generalizes the sediment supply by the D_{50} of the channel bed material.

Modeling coarse sediment transport

The implementation of the sediment transport formulae required parameterization with hydraulic and sediment information. Hydraulic information (flow velocity, shear stress, stream power, etc.) was estimated from observed values of flow discharge, which are discussed further in the next section. Boundary shear stress values were approximated as $\tau = \rho g R_h S$, where g is acceleration due to gravity, R_h is the mean hydraulic radius of the channel, and S is the mean longitudinal channel slope. This derivation of boundary shear stress is an approximation of the fluid stress borne by the channel bed and, while commonly employed in a wide range of geomorphic studies (Tucker et al. 2006; Powell et al. 2007), it uses assumptions (e.g., steady, uniform flow) that are often violated in natural flows. Hydraulic radii were computed for twenty cross sections within the lower channel system for the range of observed flows. Computed values were used to derive an average discharge-hydraulic radius relationship. The flow area and wetted perimeter were determined by routing the flow discharge through the channel network using the resistance equation of Hey (1979),

$$\frac{U}{(gRS)^{0.5}} = 5.62\log\left(\frac{aR_h}{3.5D_{84}}\right) \tag{1}$$

where U is reach-averaged flow velocity, D_{84} is grain size in which 84% of the channel bed grains are finer. The variable a is a channel shape factor defined as

$$a = 11.1\left(\frac{R_h}{D_{\max}}\right)^{-0.314} \tag{2}$$

where D_{max} is thalweg depth. This resistance equation was selected because the required input parameters of bed texture and channel geometry are known at this field site and because of its applicability to low-order channels without the presence of large roughness elements (i.e., boulders) (Thorne et al. 1985). The resistance equation predictions were validated against high-water marks measured after the conclusion of multiple flow events.

This analysis employs the sediment transport formulae using two different methods to model sediment transport at the watershed outlet: using the channel averaged GSD (GSD_A) to summarize the sediment supply and using the mean GSDs of the coarse (GSD_C) and fine (GSD_F) sediment patches that compose the channel bed to summarize the sediment supply. These different sediment supply scenarios are employed using the scaling method in Mueller (2008):

$$q_A = f\,(GSD_A) * AREA_{>2mm} \quad (3)$$

and

$$q_P = f\,(GSD_C) * AREA_{C\,>2mm} + f\,(GSD_F) * AREA_{F\,>2mm}. \quad (4)$$

Equation 3 is used to predict sediment transport using the channel-average GSD (q_A), where $f(\,)$ refers to the implementation of each sediment transport formulae and $AREA_{>2mm}$ is the fraction of the channel bed surface composed of grains > 2 mm in diameter. Equation 4 is used to predict sediment transport using the patch GSDs (q_P), where $AREA_{C\,>2mm}$ is the areal fraction of the channel bed composed of coarse patches and $AREA_{F\,>2mm}$ is the areal fraction of the channel bed composed of fine patches, with the fractional area of both types of patches further reduced by the percentage of the GSDs composed of grains less than 2 mm. Grain sizes less than 2 mm are removed from the modeling procedure, because they might not be accurately measured by the instrumentation used to evaluate sediment yield within the field site (explained in next section).

The channel-averaged GSD was taken from published values measured during the same time interval as this study (Yuill et al. 2010), which was derived from a combination of 28 bulks samples collected at monumented sections within the lower channel network.

The fractions of the channel bed area divided into the two patch categories were determined by analyzing photographic bed maps of the channel bed. The maps were constructed by splicing high-resolution photographs with a consistent scale and orientation (see Yuill et al. 2010 for a full discussion). For this analysis, the area of the coarse bed material patches was explicitly delineated and measured from the bed maps using commercial image processing software (i.e., MATLAB Image Processing Toolbox, www.mathworks.com). The area composing the fine material patches was set as the channel bed area minus the area composed of the coarse bed material patches. The mean GSD for the coarse patches was derived by a photo-sieving method discussed in Yuill et al. (2010). A GSD was computed for fifteen coarse patches after eight flow events by measuring the size of a select number (> 100) of grain composing each patch as recorded in photographic bed maps. The mean GSD for the coarse patches was approximated by taking the average value of individual GSDs. The mean GSD for the fine material patches was approximated by making a composite GSD from twelve bulk samples collected at different fine patch locations, in a similar manner as that used to compute the channel-averaged GSD.

Acquiring field measurements of sediment transport

Channelized runoff at the watershed outlet was measured using a calibrated, Santa-Rita type supercritical flume set into the channel bed (Figure 4). The flume accelerates flow velocity to prevent sediment deposition within its channel. During flow events, the flume automatically records flow stage at 15-second intervals using an integrated stilling well and float system (Smith et al. 1981).

Figure 4. Photographic diagram of the Santa-Rita type flume looking upstream (A) and a close-up photograph of the slot-sampler looking downstream (B).

A large (2 m by 4 m by 1 m) pit trap was placed immediately downstream of the flume outlet so all flow and transported sediment was directed into the trap. The pit trap was an open-top, steel-cage inset placed into the channel bed. The walls and floor were made of expended metal with openings (less than 1 mm in diameter) that let water pass through. Grain sizes small enough to become temporarily suspended within the pit trap during a flow event might have avoided entrapment if the flow over-topped the trap walls or if a turbulent splash occurred. At the conclusion of each monitored flow event, the complete trapped load was dried and transported to a laboratory for mass and grain-size analysis (by mechanical dry-sieving).

The instantaneous sediment transport rate (q_s) was not measured during this analysis. However, the mean power law relationship between q_s and excess shear stress (τ - τ_C) can be estimated in its dimensionless form;

$$q_s{}^* = \alpha \ (\tau^* - \tau_c{}^*)^{1.5} \tag{5}$$

by solving for the coefficient α in the equation

$$Q_s = \sum_{i=1}^{n} [[\alpha(\tau_i{}^* - \tau_c{}^*)^{1.5} t_i w_i] D_{50} (gRD_{50})^{0.5}] \tag{6}$$

for each runoff event, where Q_s is the observed sediment yield, i is a temporal interval with the runoff hydrograph with a constant discharge, τ is the estimated channel averaged boundary shear stress, τ_c is the critical shear stress for the D_{50} of the sediment supply, t_i is the length of interval i, w is the channel averaged wetted width during interval i, g is the acceleration of gravity, and R is the dimensionless specific gravity of the sediment. The exponent value 1.5 was attributed to the power law because this value has been found to accurately describe the exponential relationship between bed load flux and excess shear stress in many other fluvial environments where $\tau >> \tau_c$ (Garcia 2008).

4 Results

Character of channel bed material patches

Analysis of the photographic maps of the channel bed found that approximately 10% of the channel bed area was composed of coarse bed material patches. Figure 5 shows the channel-averaged GSD and the mean GSDs for the coarse and fine bed material patches within the Lucky Hills channel system. Summary statistics for the GSDs are listed in Table 2.

Observed flow and sediment values

The coarse sediment yield was retained at the watershed outlet and measured for seven surface runoff events. The magnitude of the surface flow varied with return internals estimated between fewer than 1 and 1.5 years (Table 3). The largest five flows were calculated to have produced peak shear stresses greater than that required to entrain greater than 75% of the grain sizes located within the channel bed. Peak shear stresses during the two smallest flow events (8/14/2005 and 7/27/2006) were estimated to have been too small to entrain the average D_{50} of coarse patch grains. Table 4 displays the cumulative excess shear stress borne by the full channel bed and by the fine and coarse material patches for each flow event. Excess shear stress was computed as the instantaneous shear stress

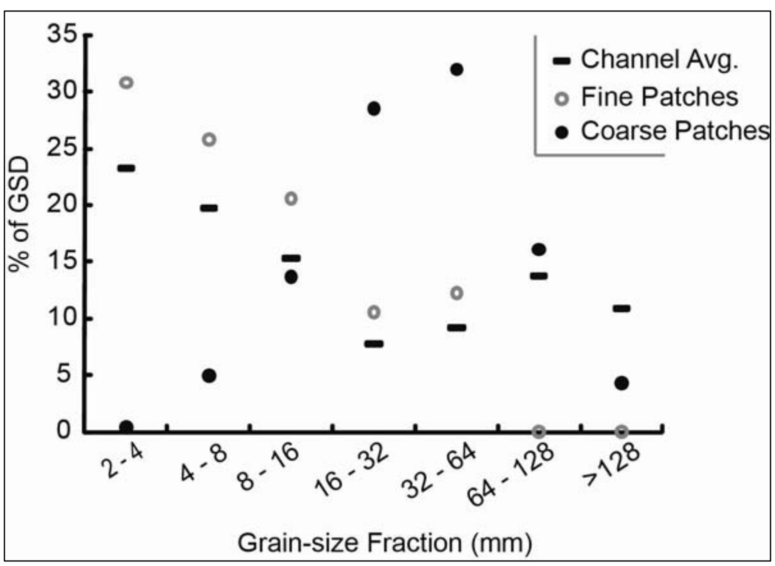

Figure 5. Mean GSDs for the full channel bed, the coarse bed material patches, and the fine bed material patches.

Table 2. Mean grain-size values for the channel bed within Lucky Hills.

Metric	Chan. Avg. (mm)	Fine Patches (mm)	Coarse Patches (mm)
Geometric Mean	3.4	1.9	36.6
Geometric St. Dev.	7.5	4.8	9.8
D_{16}	0.4	0.4	8.5
D_{50}	2.6	1.7	29.6
D_{84}	44.6	10.8	71.5
fraction sand	46%	53%	10%

Table 3. Hydrologic values for the seven flow events for which sediment yield was measured.

Flow Date	Volume (m^3)	Duration (min)	Q_p (m3 s^{-1})	τ_p (N m^{-2})	T_r (yrs)
7/27/2005	43.8	26	0.07	23.1	1.08
8/7/2005	46.1	23	0.09	26.3	1.09
8/12/2005	44.7	23	0.07	23.5	1.08
8/14/2005	20.4	35	0.03	18.1	1.02
7/27/2006	5.12	36	0.02	13.7	< 1
8/9/2006	144.4	26	0.44	45.6	1.5
9/12/2006	101.4	25	0.30	39.7	1.3

Table 4. Cumulative values of excess shear stress per unit width (τ_{CE}) and sediment yield for each flow event. The α coefficient is the best–fit value to the relationship $q_s^* = \alpha\ (\tau^* - \tau_c^*)^{1.5}$ as derived from the observed values, assuming the channel-averaged GSD as the sediment supply.

Flow Date	τ_{CE} Full Bed (N m^{-2})	τ_{CE} Fine Pat. (N m^{-2})	τ_{CE} Coarse Pat. (N m^{-2})	Observed Yield (kg)	α
7/27/2005	3.70 X 10^4	3.72 X 10^4	9.37 X 10^2	226.35	0.55
8/7/2005	2.53 X 10^4	2.30 X 10^4	9.75 X 10^2	198.63	0.48
8/12/2005	3.05 X 10^4	2.77 X 10^4	9.53 X 10^2	188.42	0.46
8/14/2005	2.51 X 10^4	2.28 X 10^4	0	52.43	0.26
7/27/2006	1.39 X 10^4	1.38 X 10^4	0	63.52	0.70
8/9/2006	2.90 X 10^4	2.61 X 10^4	1.96 X 10^3	363.38	0.38
9/12/2006	2.48 X 10^4	2.24 X 10^4	1.65 X 10^3	286.63	0.40

value minus the critical shear stress for the local D_{50} grain size. Linear regression analysis suggests that the observed values of coarse sediment yield are highly dependent on the excess shear stress borne by the coarse patch material (r^2 = 0.98) and only moderately dependent on the excess shear stress borne by the total bed GSD and the fine patch material (r^2 = 0.26 and 0.20, respectively); however, the data set is too small (n = 8) to compute a statistical significance to these trends.

Effect of sediment supply scenario on predicted sediment yield

Figure 6 shows the sediment transport rates predicted by each of the six formulae parameterized with the channel-averaged GSD, the mean fine patch GSD, and the mean coarse patch GSD for the range of shear stress occurring within the study period. The use of different sediment supply scenarios significantly impacted the estimated transport rates predicted by each transport formula which, in turn, affected the predicted coarse sediment yields (Table 5). The formulae that parameterize the sediment supply using a full GSD (i.e., *WC*, *Parker*, and *PRL*) consistently predicted higher sediment yields when the patch GSD supply scenario was used than when the channel-averaged GSD supply scenario was used. On average, the WC, Parker, and PRL formulae predicted sediment yields of 21%, 3,286%, and 12% higher, respectively, when the patch GSD scenario was used. In contrast, the formulae that parameterized sediment supply using a summary value (i.e., *MPM*, *Bagnold*, and *Schoklitsch*) tended to predict lower yield values when the patch GSD scenario was used. Using the patch GSD scenario, the *MPM*, *Bagnold*, and *Schoklitsch* formulae predicted sediment yields of 1%, 15%, and 15% less, respectively, than when using the channel-averaged GSD, on average. Also, the *MPM*, *Bagnold*, and *Schoklitch* formulae predicted that a relatively higher percentage of the sediment yield originated from the coarse bed material patches than predicted by the other formulae (during the patch GSDs supply scenario). The *EH* formula predicted 15% larger sediment yields while using the patch GSDs as the sediment supply than when using the channel-average GSD, on average. While the *EH* formula parameterizes its sediment input using a single summary value, it is differentiated from the other similar formulae because it predicts total load transport (i.e., including tractive and suspended transport) rather than solely bed load transport.

Each formula typically over-predicted the sediment transport relative to the observed values. Approximations of the relationship between the sediment transport rate and shear stress based on the observed sediment yield data were estimated using Equations 5 and 6 and the channel-averaged GSD supply scenario. This relationship is illustrated in Figure 6, and the mean α coefficient value derived from each flow event is in Table 4. The α values range in magnitude by a factor exceeding 2.5, indicating the relationship between sediment transport and shear stress exhibits significant variation between flow events.

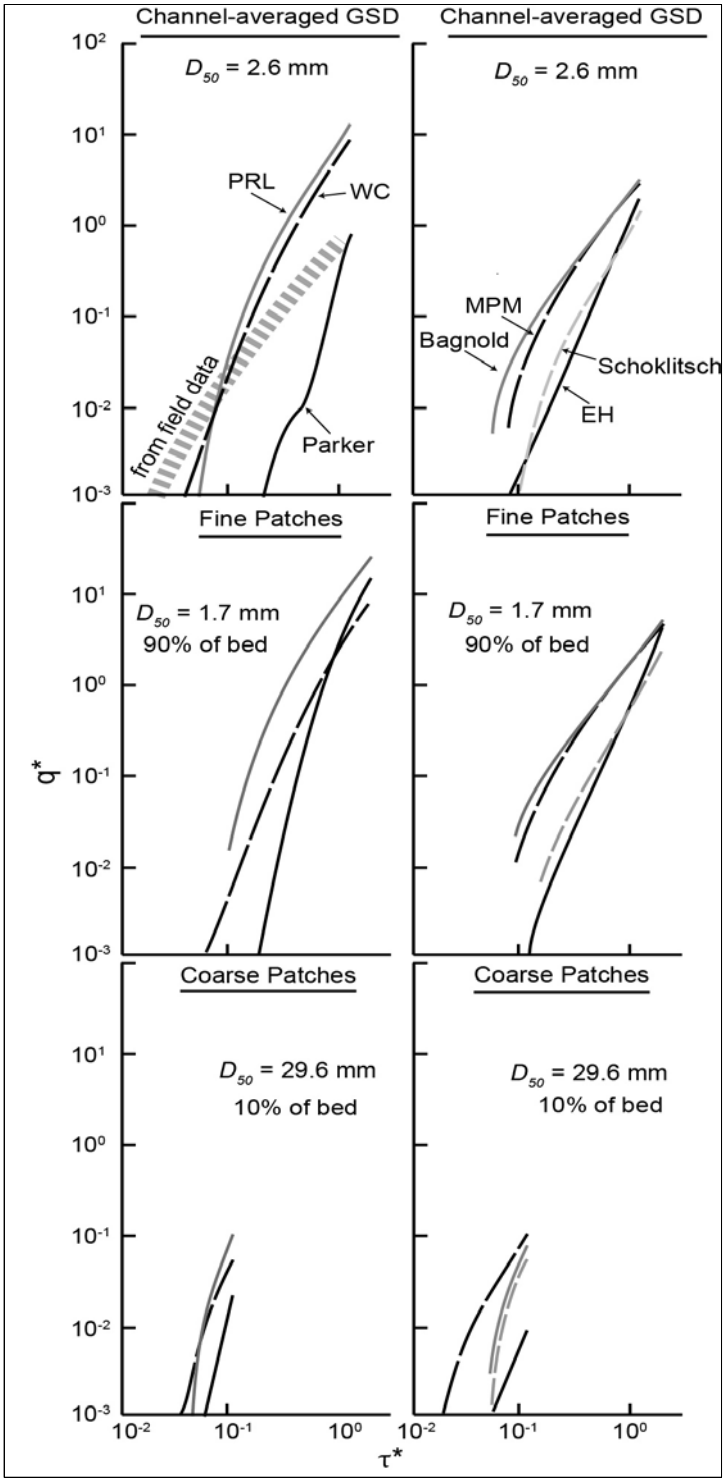

Figure 6. Relationships between the predicted sediment transport rate ($q*$) and $\tau*$ for six sediment transport formulae using the channel-averaged GSD, the GSD of the fine bed material patches, and the coarse bed material patches to characterize the sediment supply. The transport rate calculated from the observed sediment yield data is shown in the top right plot. The predicted transport rates are for grain sizes ≥ 2 mm.

Table 5. Computed sediment yields (in kgs) at the watershed outlet for the seven runoff events for each sediment transport formula. Values are given for the yields computed using the channeled-averaged GSD (Ch. Avg.) and the average GSDs of the coarse and fine bed material patches (Patches) as the sediment supply. Values in parenthesis define the percentage of sediment yield computed to have originated with the coarse bed material patches.

	Wilcock and Crowe (2003)			Parker (1990)		
Flow Date	Ch. Avg.	Patches	% change	Ch. Avg.	Patches	% change
7/27/2005	591.9	711.3 (1.0)	+20	13.8	653.7 (0.0)	+4624
8/7/2005	669.8	803.7 (1.2)	+20	15.4	758.5 (0.1)	+4809
8/12/2005	630.5	763.8 (1.0)	+21	13.6	653.3 (0.0)	+4713
8/14/2005	261.8	330.4 (0.4)	+26	5.8	173.9 (0.0)	+2917
7/29/2006	82.2	109.7 (0.1)	+33	1.1	28.6 (0.0)	+2498
8/9/2006	2090.7	2383.4 (3.0)	+14	226.9	3601.1 (0.6)	+1487
9/12/2006	1542.4	1773.5 (2.6)	+15	122.7	2517.1 (0.5)	+1951
	Powell, Reid, and Laronne			MPM (1948)		
Flow Date	Ch. Avg.	Patches	% change	Ch. Avg.	Patches	% change
7/27/2005	3157.0	3469.6 (0.2)	+10	795.6	789.3 (9.2)	-01
8/7/2005	3280.1	3550.6 (0.4)	+08	813.4	793.2 (9.9)	-02
8/12/2005	3158.1	3476.5 (0.3)	+10	804.1	791.3 (9.1)	-02
8/14/2005	1424.2	1682.7 (0.0)	+18	398.3	405.5 (6.3)	+02
7/29/2006	477.0	623.1 (0.0)	+31	154.2	161.8 (2.5)	+05
8/9/2006	8596.7	8772.1 (1.7)	+02	1927.0	1848.7 (13.0)	-04
9/12/2006	6291.9	6468.9 (1.4)	+03	1494.7	1435.6 (12.6)	-04
	Bagnold (1956)			Schoklitsch (1950)		
Flow Date	Ch. Avg.	Patches	% change	Ch. Avg.	Patches	% change
7/27/2005	987.9	826.5 (0.0)	-16	245.7	198.4 (0.0)	-19
8/7/2005	998.7	823.9 (0.5)	-18	260.5	211.2 (0.9)	-19
8/12/2005	991.1	819.8 (0.0)	-17	245.9	199.1 (0.0)	-19
8/14/2005	516.0	438.3 (0.0)	-15	101.4	85.4 (0.0)	-16
7/29/2006	218.4	190.4 (0.0)	-13	32.1	28.8 (0.0)	-11
8/9/2006	2215.2	1904.9 (6.6)	-14	844.1	747.1 (10.8)	-11
9/12/2006	1725.5	1470.4 (5.5)	-15	616.3	537.6 (9.4)	-13
	Engelund and Hansen					
Flow Date	Ch. Avg.	Patches	% change			
7/27/2005	162.7	186.4 (1.2)	+15			
8/7/2005	180.4	206.4 (1.3)	+14			
8/12/2005	162.4	186.2 (1.2)	+15			
8/14/2005	57.7	66.7 (1.1)	+16			
7/29/2006	15.8	18.4 (0.9)	+17			
8/9/2006	811.7	917.9 (1.5)	+13			
9/12/2006	555.6	629.6 (1.5)	+13			

The sediment transport rates derived from the observed yield values predicted a smaller increase in sediment transport with increased shear stress than that predicted by each formula (Figure 5). This result likely was responsible for each formula typically over-predicting the magnitude of sediment yield for each flow event. Table 6 displays the mean value of the ratio of the calculated and the observed (*C/O*) sediment yield. Ratio values between 0.5 and 2.0 are assumed to indicate relatively accurate predictions (Batalla 1997). The *Schoklitsch* and *EH* formulae produced *C/O* values within this range. The *WC*, *Parker*, *PRL*, and *EH* formulae produced higher *C/O* values using the patch GSDs sediment supply scenario than when using the channel-averaged GSD sediment supply scenario. In contrast, the *MPM*, *Bagnold*, and *Schoklitsch* formulae produced higher C/O values when the channel-averaged GSD was used as the sediment supply.

Table 6. The average *C/O* values for the sediment yields predicted for each sediment transport formula and those observed over seven flow events.

Formula	Avg. *C/O*	
	Channel-Avg. GSD	Patch GSD
WC	3.82	4.57
Parker	0.20	4.66
PRL	18.21	20.04
MPM	4.63	4.58
Bagnold	5.72	4.84
Schoklitsch	1.52	1.29
EH	1.14	1.31

Effect of sediment supply scenario on sediment yield GSD

Figure 7 illustrates the sediment yield GSD for three events as predicted by the *WC*, *Parker*, and *PRL* formulae. While the sediment yield GSDs predicted by the *Parker* and *PRL* formulae exhibited a marked dependence on the sediment supply scenario used, the yield GSDs predicted by the *WC* formula were relatively insensitive to the supply scenario. The *WC* reproduced the observed GSDs well, showing a slight tendency to underestimate the percentage of the GSD composed of grains 16-32 mm. For the relatively large flows (e.g., the 7/27/2005 and 8/9/2006 flows in Figure 7), the *Parker* and *PRL* formulae were more effective at reproducing the observed yield GSDs while employing the patch GSD supply scenario than when employing the channel-averaged supply scenario. For the smallest flow (i.e., the 8/14/2005 flow in Figure 7), the *Parker* formulae was most effective at reproducing the observed yield GSD using the channel-averaged GSD supply scenario. The *PRL* formula consistently over-predicted the percentage of the sediment yield composed of grains > 32 mm for each flow event, especially when the channel-averaged GSD was considered the sediment supply.

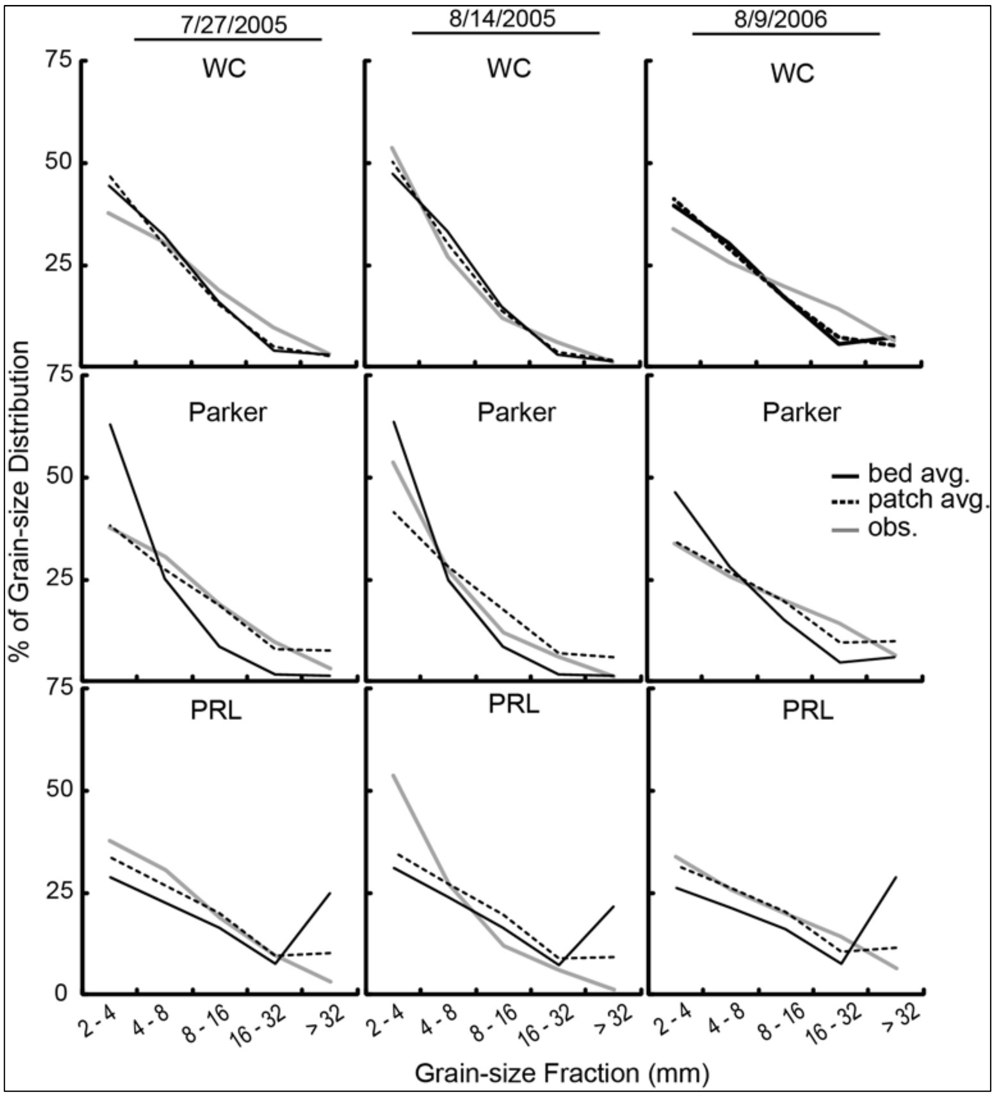

Figure 7. The predicted and observed GSD of the sediment yield for three runoff events using three sediment transport formulae and two sediment supply scenarios.

5 Discussion

This study considers two different sediment supply scenarios for incorporation into a selection of sediment transport models: using the channel-average GSD as the sediment supply and using a spatially-scaled combination of a relatively coarse and a relatively fine GSD as the sediment supply, which reflects the fact that the channel bed is arranged in coarse and fine textual patches. The mobility of an individual grain resting on the surface of the channel bed is based on its absolute size as well as its relative size within the GSD of the local bed material (Andrews 1983). The scenario that characterizes the bed material using two GSDs likely describes the local GSD more accurately over a larger percentage of the channel bed than the scenario only using one GSD. However, its use does not systematically increase the accuracy of the predicted sediment transport rates in this study.

The use of the patch GSDs typically altered the sediment yield 10-20% from that predicted using the channel-averaged GSD supply scenario. The predictions computed with the *MPM* formula were less sensitive than the other formulae to altering the sediment supply scenario, while on average the *Parker* formulae was much more sensitive. Likely, other factors beyond the method used to characterize sediment supply influenced each formula's predictive accuracy as observed in the Lucky Hills fluvial system. The tendency for each formula to over-predict transport relative to the observed values could indicate that coarse sediment transport in Lucky Hills was affected by supply limitations. Transport formulae predict the theoretic transport capacity of the flow, which equals the transport rate absent of any general supply limitations (Bravo-Espinosa et al. 2003). Typically, ephemeral channels in alluvial watersheds are assumed to be relatively sediment rich fluvial systems (Laronne et al. 1994; Reid and Frostick 1997). Further, field observations during the study period never found any well established signs of sediment depletion (e.g., exposed bed rock, incision, scour). However, laboratory studies have found that alluvial channels may respond to sediment supply reductions by coarsening their beds, at the reach scale or in spatially explicit patches (Dietrich et al. 1989; Nelson et al. 2009). It might be that the spatial structure of the patchiness in Lucky Hills is dependent on spatial variations in the sediment supply and that the coarse patches have evolved in areas experiencing limited sediment supply relative to other areas around the bed. The cumulative effect of these local supply limitations might result in the sediment transport rates falling below the transport capacity predicted by each formula at the watershed outlet.

The range of calculated-to-observed values (*C/O*) computed for the sediment transport formulae tested are typical of that reported in past analyses in other fluvial systems, such as perennial gravel (Gomez and Church 1989; Bravo-Espinosa et al. 2003; Duan et al. 2006), perennial sand-gravel (Batalla 1997), and ephemeral gravel channels (Reid et al. 1996). This is noteworthy because Lucky Hills is significantly different than the fluvial systems in which most formulae were derived, specifically in reference to its very poorly sorted, sand-gravel channel bed material and ephemeral flow regime. This result suggests the sediment transport mechanics replicated by the set of formulae employed by this study are not necessarily different in ephemeral channels with sand-gravel beds than in other fluvial systems.

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Appendix A: Bed load formulae equations

A list of the full set of equations, using the notations from their original sources, for three bed load formulae referenced in this study:

Wilcock and Crowe (2003)

$$W_i^* = \frac{Rgq_s}{F_i u_*^3} = G(\varphi)$$

$$\varphi = \varphi_{sgo}(\frac{D_i}{D_m})^{-b}, \varphi_{sgo} = \frac{\tau_{sg}^*}{\tau_{ssrg}^*}, \tau_{sg}^* = \frac{u_*^2}{RgD_m},$$

$$\tau_{ssrg}^* = 0.021 + 0.015\exp(-14F_s)$$

$$G(\varphi) = 14(1 - \frac{0.894}{\varphi^{0.5}})^{4.5} \_for\_\varphi \geq 1.35$$

$$G(\varphi) = 0.002\varphi^{7.5} \_for\_\varphi < 1.35$$

$$b = \frac{0.69}{1 + \exp(1.5 - \frac{D_i}{D_m})}$$

Parker (1990)

$$W_i^* = \frac{Rgq_s}{F_i u_*^3} = 0.00218G(\phi)$$

$$\phi = \omega\phi_{sgo}(\frac{D_i}{D_m})^{-0.0951}, \phi_{sgo} = \frac{\tau_{sg}^*}{\tau_{ssrg}^*}, \tau_{sg}^* = \frac{u_*^2}{RgD_m}, \tau_{ssrg}^* = 0.0386$$

$$G(\phi) = 5474(1 - \frac{0.853}{\phi})^{4.5} \_for\_\phi > 1.59$$

$$G(\phi) = \exp\left[14.2(\phi - 1) - 9.28(\phi - 1)^2\right]\_for\_1.0 \leq \phi \leq 1.59$$

$$G(\phi) = \phi^{14.2} \_for\_\phi < 1.0$$

$$\omega = 1 + \frac{\sigma}{\sigma_0(\phi_{sgo})}[\omega_0(\phi_{sgo}) - 1]$$

Powell et al.

$$W_i^{\ *} = \frac{Rgq_s}{F_i u_*^{\ 3}} = G(\phi)$$

$$\phi = \frac{\tau_{si}^{\ *}}{\tau_{sci}^{\ *}}, \tau_{si}^{\ *} = \frac{u_*^{\ 2}}{RgD_i}, \tau_{sci}^{\ *} = 0.03\left(\frac{D_i}{D_{50}}\right)^{-0.74}$$

$$G(\phi) = 11.2(1 - \frac{1}{\phi})^{4.5}$$

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14. ABSTRACT

Seven 1-D sediment transport formulae are employed to predict coarse sediment transport in a low-order, ephemeral channel with patchy bed material. Sediment transport is modeled through two different methods to characterize sediment supply: by using a channel-averaged grain-size distribution (GSD) and by using the mean GSDs from the relatively coarse and fine textured patches that compose the channel bed.

Modeling results show that the two different characterizations of the sediment supply produce significantly different values of predicted coarse sediment yield. The relative differences in the predicted yield values are dependent on the assumptions of each formula, including how the sediment supply is parameterized within the model. Modeled sediment yield values are contrasted to observed values for seven flash flood-type runoff events. The formulae accuracies typically are comparable to past analyses in fluvial systems more reminiscent of the hydraulic environments in which the models were derived (perennial flow, gravel-bed material).

Study results reaffirm that the method by which sediment supply is characterized significantly impacts the performance of sediment transport formulae and that a single GSD might not adequately describe the sediment supply originating from patchy beds.

15. SUBJECT TERMS
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